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In Search of Efficient Walking Robots

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ABSTRACT

With the recent conflicts in Afghanistan and Iraq, it is increasingly evident that the demands of warfare are changing and the need for innovative mobility systems is growing. In the rough, unstructured terrain that the soldiers encounter, they have reverted to using mules and donkeys to move stealthily and quickly. In light of the growing need for autonomous systems, the Army is looking at the possibility of legged mobility options such as gasoline powered quadrupeds to traverse the off-road terrain. As technology advances, the era of military bipeds may well be in sight. However, current bipedal robotic technology is far too inefficient for battlefield use. Much of this inefficiency stems from actuated control of each limb's motion throughout the entire gait cycle. An alternative approach is to exploit the passive pendular dynamics of legs and legged bodies for energy savings. This paper compares and contrasts fully-actuated walking with passive walking. Simulations of passive and quasi-passive walking are analyzed to evaluate their stability regions and their initial responses on uneven terrain functions are compared.

INTRODUCTION

One of the first "walking machines" was a toy developed by G.T. Fallis (Figure 1), patented in January 1888. A description from the patent document provides insight into the mechanics of passive dynamic walking.

> This invention consists in a toy or figure which may be designed to simulate … the human frame… and which is of a combined pendulum and rocker construction, whereby when placed upon an inclined plane it will be caused by the force of its own gravity to automatically step out and walk down said plane...

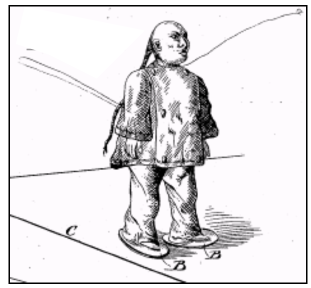

Figure 1: Sketch of Fallis' Walking Toy

The notion of 'autonomous' mechanical creations originated even earlier with the famous Vaucanson's Digesting Duck and other automata of the 18th century (see Figure 2). The highlight of this era of mechanical wonders was Von Kempelen's The Turk. Although, later proved to be a hoax, this intriguing automaton initiated the foundations for artificial intelligence and emphasized the fascination of a thinking, mechanical human.

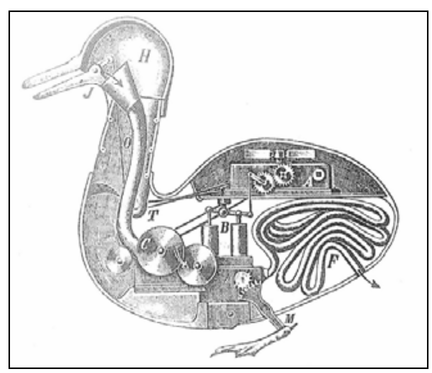

Figure 2: Theoretical View of Vaucanson's Digesting Duck

The initial definition of robotics began to take form in the 1920's with the first usage of the word robot in Karl Capek's *Rossum's Universal Robots* to describe something built to perform dull, dangerous, and dirty tasks. The first commercial robot produced did just that-it took the position of an assembly-line worker, working heated die-casting machines at General Motors. The robot's name was Unimate, created by George Devol and Joseph Engelberger in 1956.

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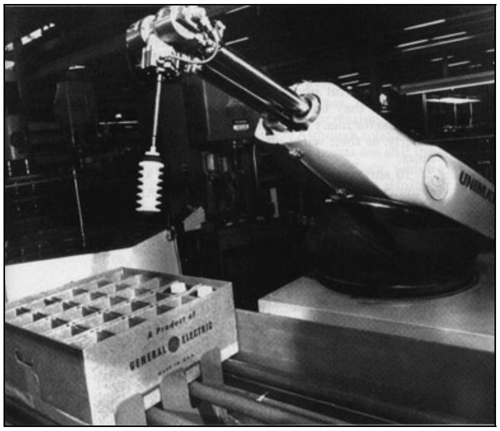

Figure 3: Unimate Robot

Unimate was operated by a series of programmable motors and actuators to control its movements. It falls into the category of robots known as set-point controlled, whose main goal is to follow a prescribed path with minimal error through continuous actuation. The majority of robotics has been focused in this area with such stars as Honda's Asimo and Sony's Qrio shown below.

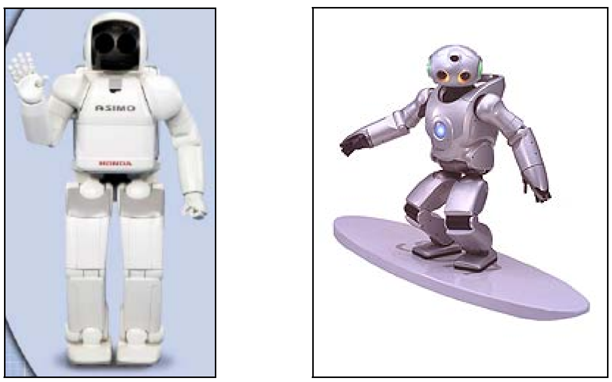

Figure 4: Honda's ASIMO and Sony's Qrio Biped Robots

Albeit the idea of passive walking has been around for a while, Tad McGeer introduced the theory and renewed interest in the topic, creating a new avenue of robotics research based on dynamics. Using simplistic models or rimless wheels and double inverted pendulums, McGeer was able to mimic human gaiting.

One might wonder why look at walking robots when wheels are an efficient and fast way to locomote from here to there. Wheels are better suited for on-road applications, but legged robotics has an advantage in the off-road arena because of its small footprint and low ground pressure. Due to the recent conflicts in the Middle East and technological advances, military interest in robotics for off-road applications has heightened. In a *Foreign Affairs* article by Donald Rumsfeld in 2002, he describes the new war zone:

> [The troops] sported beards and traditional scarves and rode horses trained to run into machine gun fire. They used pack mules to transport equipment across some of the roughest terrain in the world, riding at night, in darkness, near minefields and along narrow mountain trails with drops so sheer that, as one soldier put it, "it took me a week to ease the death grip on my horse."

One of his conclusions was that "It shows that a revolution in military affairs is about more than building new high tech weapons… it is also about new ways of thinking and new ways of fighting." Robotics is one of those 'new ways' and is taking shape with the deployment of several tele-operated systems such as the PackBot.

Currently, the Army is working with several companies to explore the possibility of using walking robots for military use. One prototype uses a bipedal gait to carry a generator for dismounted troops. It is this type of robot that motivates our discussion: How can we improve the mobility and fuel efficiency of a walking robot?

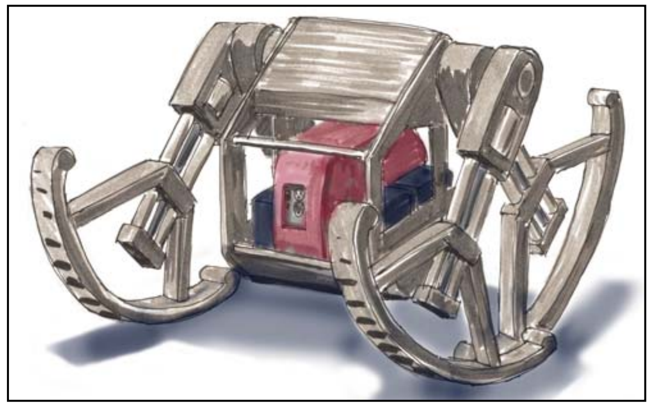

Figure 5: Concept Drawing of Prototype Robotic Mule

One of the possibilities is to use passive dynamics. Some of the advantages of a passive dynamic legged machine are that it requires no energy on a sloped surface compared to a set-point controlled robot. Looking at a quasi-passive walker to accommodate positive and level terrain negotiation requires a smaller power supply to provide the necessary actuation to overcome gravity and the robots own inertia because of the utilization of the natural dynamics of pendular motion. Each movement of the set-point controlled robot is articulated with a host of motors and actuators that controls every movement and requires more power because there are no underlying dynamics to provide movement during a step.

The passive walker is inherently more robust to variations in the surroundings, such as perturbations in the ground, as long as it is given some time to adjust. In example, imagine that a person is walking and stubs their toe on a raised piece of sidewalk. Depending on the speed of the person, they will typically be able to catch themselves before falling. If the changes are too drastic then there could be problems (imagine the same person is running at top speed and not paying attention). The passive walker can also handle larger variations in payloads. If a set-point controlled robot wants to increase its payload, the motors need to be scaled accordingly while the passive walker can add weight with little change in the power requirements.

The small motors and actuators needed for the quasi-passive walker, contribute less noise and a lower heat signature than the set-point controlled robot with its host of motors and actuators. Both noise and heat are important considerations for stealth applications in the military.

Although there are many advantages to passive walkers, there are also disadvantages. Walking machines have been around since the late 1800's but passive dynamic walking has not had the same amount of research resources devoted to it like set-point controlled robots. With companies like Honda, Toyota, and Sony investing in set-point control, the technology in that area is much more advanced. Another issue is the variety of contact problems possible ranging from toe stubbing, foot scuffing, tripping, or all out collapse. It is difficult to recover from these without the actuation/motors of set-point controlled robots. The passive walker is also very sensitive to initial conditions. Without a stable gait, the passive walker is highly susceptible to disturbances.

Overall, sensor technology is lacking for both passive and set-point controlled walkers. Sensors are necessary to gauge the terrain and surrounding environment to provide feedback to the robot (think of a person's eyes, ears, touch, taste, and smell senses).

ANALYSIS

To gain insight into how a passive dynamic walker and a passive dynamic robot following a prescribed path compare to each other, a simulation was created to use the recorded swing leg position, q2, to provide a torque input to the quasi-passive walking model. Figure 3 shows a brief schematic of the simulation.

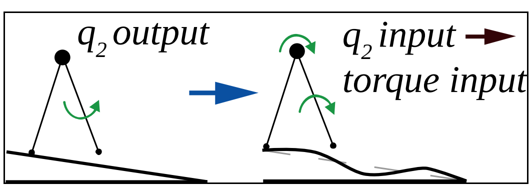

Figure 6: Diagram of Problem Setup

A simple controller was implemented to create a torque to drive the q_2 angle to match the prescribed q_2 of a completely passive walker in its stable gait. The torque was introduced at the hip as an external input to the system.

A curved ground with an average equal to gamma was introduced to test the walkers' ability to handle a perturbation using the same initial conditions for the sloped ground. For extended simulations, a simple sloped ground continues the curved ground at half of the original average slope, γ.

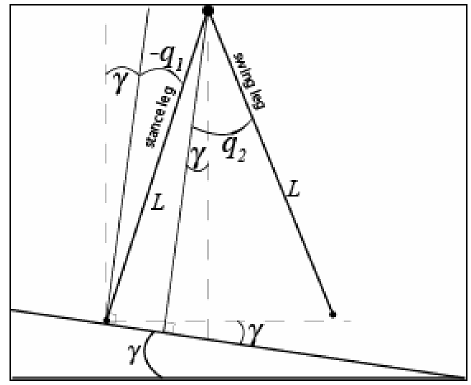

Figure 7: Passive Walker Diagram

The basic equations of motion for a simplified passive dynamic walker are presented below (1). They are based on a double inverted pendulum system with β representing the ratio of the mass at the foot to the mass at the hip. The model used for the simulations is a more complicated walker with inertial properties for the hip mass and leg but the assumptions of a frictionless pin at the hip and rigid legs are still considered.

$$\begin{bmatrix} 1+3\beta(1-\cos(q_2-q_1)) & -\beta(1-\cos(q_2-q_1)) \\ \beta\cos(q_2-q_1) & -\beta \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix}+ \begin{bmatrix} -\beta\sin(q_2-q_1)((\dot{q}_2-\dot{q}_1)^2-2\dot{q}_1(\dot{q}_2-\dot{q}_1) \\ \beta\dot{q}_1^{\,2}\sin(q_2-q_1) \end{bmatrix}+ \begin{bmatrix} (\beta g/l)[\sin(2q_2-q_1-\gamma)-\sin(q_1-\gamma)-g/l\sin(q_1-\gamma) \\ (\beta g/l)\sin(2q_2-q_1-\gamma) \end{bmatrix}= \begin{bmatrix} -\tau_{hip} \\ \tau_{hip} \end{bmatrix} \tag{1}$$

The momentum equations based on the simplified equations of motion are shown in (2).

$$\begin{bmatrix} q_1 \\ q_2 \\ u_1 \\ u_2 \end{bmatrix}^+ = \begin{bmatrix} -1 & 0 & 0 & 0 \\ -3 & 0 & 0 & 0 \\ 0 & 0 & \cos 2\theta & 0 \\ 0 & 0 & -\cos^2 2\theta & 0 \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ u_1 \\ u_2 \end{bmatrix}^- \tag{2}$$

A list of the variables used in the simulation and their values are presented in the table below. These values represent an average person's anthropometric measurements, after normalizing by leg length and mass, to non-dimensionalize the model.

Variable	**Meaning**
L = 1	Leg length
Gamma = 0.016	Ground slope
Il = 0.017	Inertia of the leg
C = 0.645	Distance from foot to leg COM
M = 0.16	Mass of the foot
R = 0	Radius of the foot
Mp = 0.68	Mass of the pelvis
Ip = 0.01	Inertia of the pelvis
G = 1	Gravity

Table 1: Walking Simulation Variables

The code used for the simulations was adapted from passive dynamic walker code originally developed by Professor Arthur Kuo (University of Michigan). The program integrates the differential equations of motion, stops the simulation when the swing leg connects with the ground (ignoring the first swing leg interaction with the surface when the walker is near vertical- foot scuffing), and accounts for momentum loss when the foot impacts ground. Figure 8 shows the basic flow of the program.

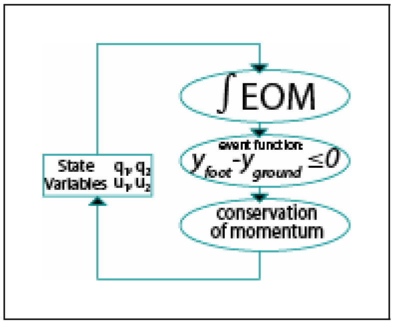

Figure 8: Passive Walker Program Flow

One addition is a new event function that compares the global y position of the foot with the global y position of the ground and stops the integration when the foot position is less than or equal to the ground at the same x position, ignoring foot scuffing. A stable fixed point was also necessary. To find the stable fixed point, the simulation ran until the walker settled into its stable gait. A stable gait is one in which the walker will return to its periodic motion after a slight perturbation. Stability is evaluated through the Floquet multipliers (discrete cycle-to-cycle measurements of amplification or attenuation of perturbations) of the partial derivative of the return values (the initial values for the next step) from the state variables of one step. An example of the state variables for a stable fixed point on a slope of 0.016 is provided in the table below.

Variable	Stable Value
q_1	0.2176 radians
q_2	-0.2176 radians
u_1	-0.2492 radians/sec
u_2	-0.1970 radians/sec

Table 2: Stability Values for γ = 0.016

Another addition was a torque at the hip in the equations of motion. To ensure that the actuated walker follows the recorded state vector of the passive walker accurately, a simple proportional-derivative controller was created.

CONTROLLER DESIGN

The controller design began with a linearized model of the equations of motion. The linearization was done using the standard Lyapunov method. The equations of motion are set up in the form of the robot equation (3) and then solved for the accelerations (4).

$$M\ddot{\theta} + V(\theta,\dot{\theta}) + G(\theta) = \tau \tag{3}$$

$$\ddot{\theta} = M^{-1}\{\tau - V(\theta,\dot{\theta}) - G(\theta)\} \tag{4}$$

The first step is to transform the equations into state space form. The state variables involved are q_1 (angle of the swing leg), q_2 (angle of the stance leg), u_1 (velocity of the swing leg), and u_2 (velocity of the stance leg). The conversion to state space was done through the change of variables below.

$$\begin{aligned} q_1 &\to x_1 \\ q_2 &\to x_2 \\ u_1 &\to x_3 \\ u_2 &\to x_4 \end{aligned} \tag{5}$$

Once the equations are converted to state space, set the state derivatives equal to zero. After setting the state derivatives and input (torque at the hip) equal to zero, the equations are solved for x_1 and x_2, the equilibrium point. Several different solutions came out of the equations because of the sine and cosine relationships. The solution that is the closest to the typical operating point is chosen as the equilibrium point. The solutions correspond to the following positions in the figure below. Solution b (γ, $-\pi + \gamma$) is the equilibrium point for the system.

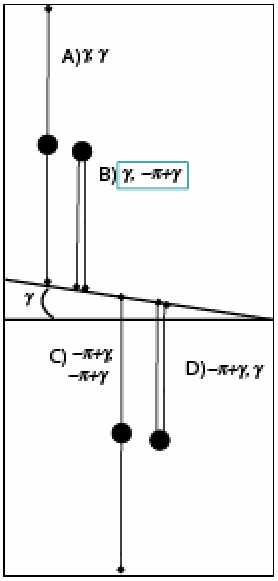

Figure 9: Equilibrium Positions of Double Pendulum

The Jacobian of the state space is evaluated at the equilibrium point to find the state space matrices A and B. The C matrix is created to track the variable of concern, which, in this case, is the swing leg angle (x_2). The subsequent state space matrices were analyzed in MATLAB to create a simplified controller. The final controller is a proportional-derivative controller and its transfer function is provided in (6).

$$tf = 6.8s + 20 \tag{6}$$

RESULTS

The difference between the original recorded state variable of q_2 and the torque driven model over one step is shown in Figure 10. The controller does a fair job of tracking the original path as the error is on the order of magnitude of 10E-04.

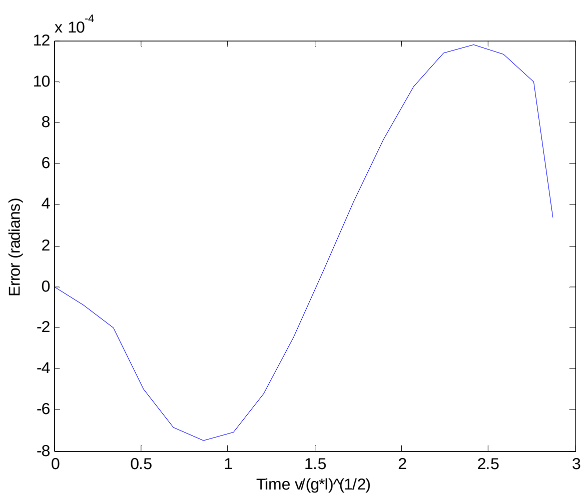

Figure 10: Error in q_2 For One Step, γ = 0.016

Initially, the models were run with various sloped surfaces to evaluate their stability. The tests produced the curves in Figure 11, with markers representing the q_1 fixed point values. The variable q_1 was chosen for this study because q_1 and q_2 are symmetric upon impact. There were four sets of recorded angles (γ = 0.01, 0.016, 0.02, and 0.03) from the passive walker used as references to drive the torque-driven walker. Generally, as the quasi-passive walker is referenced to steeper slopes, its range of application slopes increases. It must be noted that this is a limited data set and as the slope is increased the robustness will decrease at some point. More tests need to be conducted to find the point at which the range decreases. Another interesting result to note is after γ = 0.04 for the passive walker, a stable period 2 gait develops. Multi-periodic gait fixed points were averaged for the graphical representation. Smaller increments of slope increases need to be evaluated to find the stability limit of the passive walker. Adding the torque and the simple proportional derivative controller extends the range of the passive walker to γ = 0.075 on the coarse grain of the study whereas the passive walker was unstable beyond γ = 0.05.

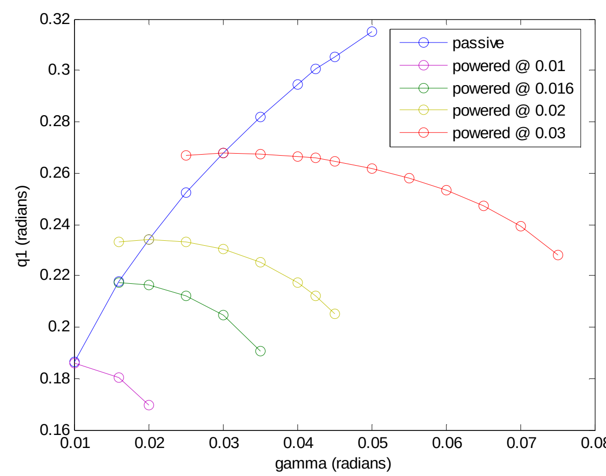

Figure 11: q_1 of Fixed Points Parametric Study on Sloped Ground

To understand how a change in the ground function affects the two walkers, the group introduced a sine wave into the slope. The idea was to keep the curve's average the same as the slope. From initial observations, the ground could change local slope as long as the change was small enough such that the passive walker could adjust within a couple of steps. A simple function was chosen for testing with a slight slope (7). Comparing the two, the quasi-passive walker did not have as much variation in its step length.

$$y = 0.01(\cos(x-1) - \tan(\gamma)\cdot x) \tag{7}$$

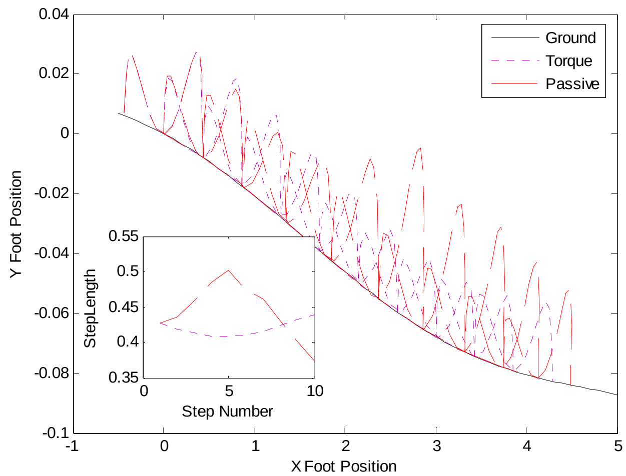

Figure 12: Foot Placement and Steplength for 10 Steps on Curved Ground, γ = 0.016

The addition of the feedback controller and torque 'smoothes' the walker as it traverses the curved slope. The torque history for the quasi-passive walker is provided in figure 13. The torque was limited to $m_{foot} \cdot g \cdot l$. Realistically, the torque will not be as discontinuous. The figure provides an idea of the magnitude of the torques and their frequency (histogram in lower left corner). The torques are centered around zero, so the controller is making only minor adjustments over the duration of the step.

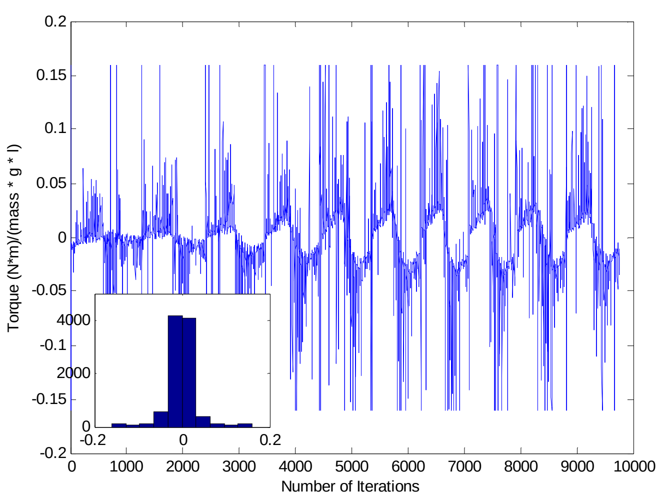

Figure 13: Torque History for 10 Steps on Curved Ground, γ = 0.016

FUTURE WORK

As noted in the paper, these are preliminary results. The group is interested in performing a set of parametric studies over a larger range with finer resolution, addressing the stability conditions and perturbed ground amplitudes. Other issues to address are the realism of the torque input into the system. Some smoothing should be employed to provide a more continuous torque. Many of the fixed points were found experimentally through increasing the number of steps until a discernible pattern was observed. Further work needs to be done to improve the search method for these fixed points.

Other research topics include using the torque for a portion of the step and allowing the pendular dynamics of the walker to do the rest.

CONCLUSIONS

This study shows some promising results through the use of a simple proportional-derivative controller to create a robot driven from recorded state variables. Employing feedback in a system typically enhances the performance and makes it less susceptible to disturbances. This is evidenced in the increased range of the quasi-passive walker to γ = 0.075 in the simple slope case. In the curved slope experiment, the step length is more uniform for the quasi-passive robot than in the purely passive case. Comparing the animations of the two models shows the quasi-passive walker powering over the slope. It is also worth noting that the quasi-passive walker simulation takes at least one hundred times longer to run. Although the torqued walker is more robust, there are still many disadvantages to consider.

ACKNOWLEDGEMENTS

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